MANAGEMENT OF BONE DEFECTS
A Review of Available Techniques

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INTRODUCTION

Trauma, neoplasm, congenital defects, infection and failed arthroplasty are all capable of creating large bony defects. Achieving the goals of osseous reconstruction of these defects, namely, sustaining bone length and securing bony union, remains a challenge to the orthopaedic surgeon.

Primary limb shortening, which is generally well tolerated in the upper limb without significant effects on cosmesis or function, and various amputations of both the upper and lower extremity are among many techniques in the surgeon's armamentarium. The goal of this article, however, is to review reconstructive procedures available once the surgeon has chosen to salvage the limb and maintain skeletal length.

CLASSIFICATION

Various techniques are individually categorized in Table 1. The entire reconstructive effort, however, may employ combinations of several methods, e.g., prosthesis + allograft ("alloprosthesis"), bone transport + autograft, etc. This discussion will focus on cancellous autogenous grafting, structural autogenous grafting (particularly with reference to various uses of the fibula) and distraction osteogenesis. In addition, various uses of allograft, xenograft, biomaterials and prosthetic implants will be reviewed.

GRAFTING TECHNIQUES

Cancellous Autografting

Early surgeons initially used cortical bone,[1] but after half a century of surgical practice there seemed to be near universal agreement that cancellous bone was superior. Nonvascularized cortical autograft, while it may provide immediate bony support, has the disadvantages of slow union, high incidence of fatigue fracture, and the probability that total revascularization and replacement may never occur. Conversely, cancellous graft has greater capacity to induce osteogenesis, revascularizes easier, and matures and remodels faster. Though stress hypertrophy occurs slowly, the new segment can be augmented by supplementary grafting.[30]

TABLE 1
TECHNIQUES FOR RECONSTRUCTION OF BONE DEFECTS

I. Grafting
  A. Autograft
    1. Cancellous
      a. open
      b. closed
    2. Structural
      a. fibular transfer
      b. non-vascularized bone
      c. vascularized bone
    3. Autoclaved
  B. Allograft
  C. Xenograft
II. Distraction Osteogenesis
  A. Bone transport
    1. Monofocal
    2. Bifocal
    3. Fibular transfer
  B. Compression-distraction
III. Biomaterials
  A. Demineralized bone matrix
  B. Ceramics
IV. Prosthetic Implants

The fragments of cancellous bone should have one dimension less than five mm so that nutrients can diffuse to all the osteoblasts.[4] These fragments can be used in either an open[33] or closed technique. With the open technique, union is obtained first and the skin defect is allowed to epithelialize spontaneously or with the aid of a split thickness graft. With the closed method stable soft tissue coverage is obtained prior to bone grafting.

Open Cancellous Grafting (Papineau)

For both techniques the early steps of treatment are the same and include meticulous debridement of all necrotic bone and soft tissue and stabilization of the skeleton (e.g., external fixator, intramedullary nail, plate, tibiofibular synostosis). In the open technique, a bed of granulation tissue allowed to form. Cancellous graft is then packed into the skeletal defect without soft tissue coverage. The bed of granulation tissue revascularizes the bone graft and the defect is allowed to epithelialize spontaneously or a split thickness graft is applied. (Figure 1A-F).

Green and Dlabl[15] used this technique in fifteen patients

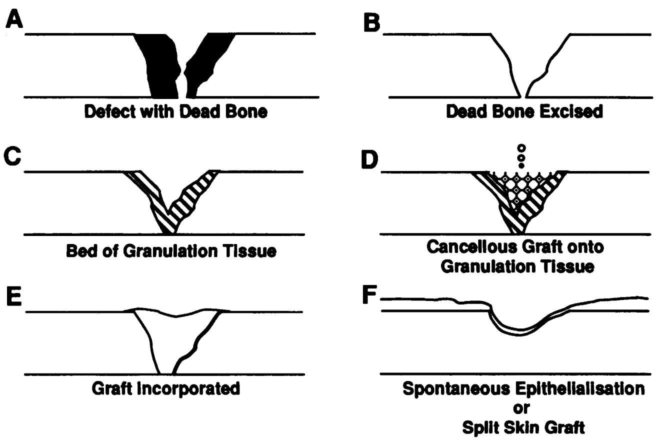

Figure 1
Open cancellous grafting

aged twenty-one to sixty-seven for septic nonunion of various long bones. Following adequate debridement, resultant bone defects ranged from 1.5 to eight cm. Union was established in thirteen of fifteen cases; two eventually required amputation. Important technical points stressed by the authors included: 1) thorough debridement, 2) adequate skeletal stabilization (biplaner external fixation was recommended), 3) waiting until all exposed bone is covered with granulation base prior to grafting (average time: four weeks in this series), 4) maintenance of the viability of the transplanted bone tissue by immersing it in a physiologic irrigating solution, and 5) inserting a bone graft tissue mass larger in diameter than the bone being replaced. The authors concluded that this technique is not suitable for defects greater than nine cm since a limited volume of cancellous bone is available for reconstruction.

Malkawi, et al,[28] reported on a similar series of thirteen patients managed with open cancellous grafting. Defects, following debridement, averaged 4.3 cm (range two to ten cm). Union and eradication of infection were achieved in all patients, though functional results were considered poor in four and fair in four due to shortening or poor ankle motion. The authors concluded this technique would achieve good results even in such unfavorable conditions as those encountered in infected segmental bone defects, providing a well vascularized bed and adequate stability are achieved prior to grafting.

Although the open technique is less demanding and is associated with less potential morbidity than other techniques, disadvantages do exist. In general, open grafting is poor for defects: 1) over four cm, 2) with poor surrounding muscle and, 3) with total loss of bone substance (diaphysectomy).[37] The procedure will not work if the local blood supply is inadequate to support formation of granulation tissue. Finally, the technique provides less durable skin coverage and intrinsic bone strength is slow to develop.[31]

Closed Cancellous Grafting

Following debridement, stable soft tissue coverage in the form of rotational, cross leg pedicle or free flaps is obtained prior to grafting. Free tissue transfer is best for management of large defects created following debridement after trauma or infection.[13,31] Free tissue, because of its potential bulk and unlimited mobility, allows for much more radical debridement of devitalized or infected tissue. Unlike local flaps, free tissue can cover massive defects, is not limited by the muscle's arc of rotation, and does not further compromise adjacent recipient tissue. Also, a transferred tissue flap with microvascular anastamoses is highly vascularized as opposed to local flaps, which are rendered relatively ischemic in their distal portion. In contrast to cross leg flaps, in which increased blood flow is only transitory, free flaps add permanent supply to the region.[39]

Regardless of the soft tissue coverage chosen, increased vascularity in the recipient bed aids in rapid incorporation of cancellous grafts. Successful healing has been demonstrated in several case series where diaphyseal defects averaging five cm,[28] 8.8 cm,[30] and ten cm[8] have been successfully reconstructed in multi-staged procedures which include obtaining stable soft tissue coverage followed by massive autogenous grafting. Drawbacks of this technique include the need for multiple operative procedures (usually three to five) and potential soft tissue and bony donor site morbidity. Recent reports seem to favor closed over open grafting, though the best results have a healing index* of only one cm per month.

$$\text{*healing index} = \frac{\text{length of defect (cm)}}{\text{treatment time (months)}}$$

STRUCTURAL AUTOGRAFTING

Various uses of the fibula have been employed in the management of segmental defects. These techniques, including fibular transfer, free nonvascularized fibular autograft, tibiofibular synostoses and free vascularized fibular autograft, provide useful models for discussing various uses of structural autograft. Fibular transfer was first described by Hahn in 1884 for management of congenital pseudoarthroses. Huntington then modified the technique to a two stage transfer in 1905 for the management of traumatic defects.[30] This modification was later employed by Carrell[6] for use in tumor surgery. (Figure 2). Fatigue fracture and nonunion, which may compromise further efforts at reconstruction, were frequent problems with these techniques. Also, these methods cannot be considered when the peroneal vascular pedicle is the sole supporting artery to the lower limb and foot.[31]

Tibio-fibular synostoses

Multiple techniques have evolved which attempt to bridge a tibial defect by creation of a proximal and distal

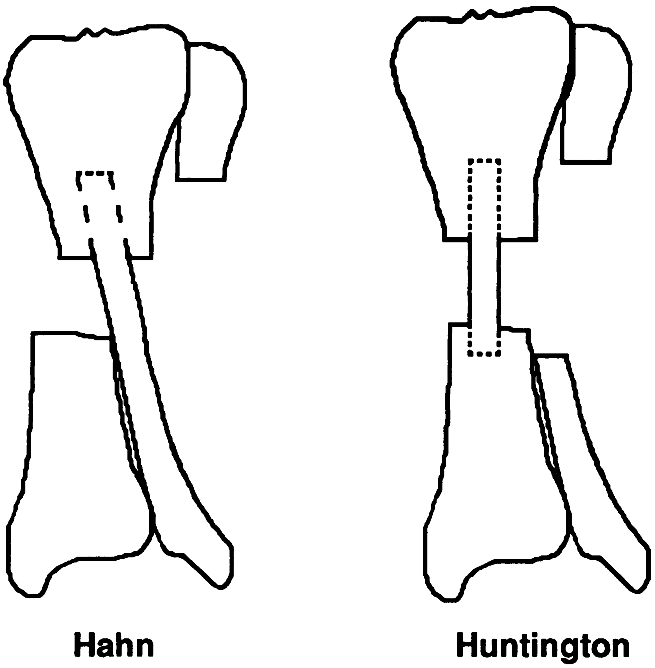

Figure 2
Hahn's fibular transfer and Huntington's two stage modification

tibio-fibular synostosis (Figure 3). Nonunion, unremitting infection and amputation were common sequelae following many of the early single stage procedures. Subsequent staged procedures have achieved much higher success rates. Basic principles, as outlined by Maurer and Dillon,[30] include: 1) control of infection and stable soft tissue coverage, 2) stabilization of the tibia by transfixing the fibula proximally and distally with screws, and, in large defects (> 12 cm), spanning the tibial gap with a plate, 3) increase structural strength of the construct by bridging the tibial defect with cancellous graft or reinforce the fibula spanning the defect with cancellous graft, and 4) prolonged, protected weightbearing in a brace.

Employing these principles, defects ranging five to fifteen cm were successfully bridged in patients who had severe soft tissue trauma, local sepsis, and were otherwise candidates for amputation. Five to seven procedures, separated roughly by three months, were required for each patient. No implant failures, fatigue fractures or chronic infection were noted at a mean follow-up of 5.5 years. The tibio-fibular synostosis, while avoiding areas of sepsis, functions as an internal splint and provides a stable environment for incorporation of cancellous graft in the tibial defect and/or around the bridging segment of fibula. This technique is suitable for defects greater than three cm, provided that a stable soft tissue cover is obtained first. In general, defects under three cm are more easily handled with a simpler posterolateral graft.[14]

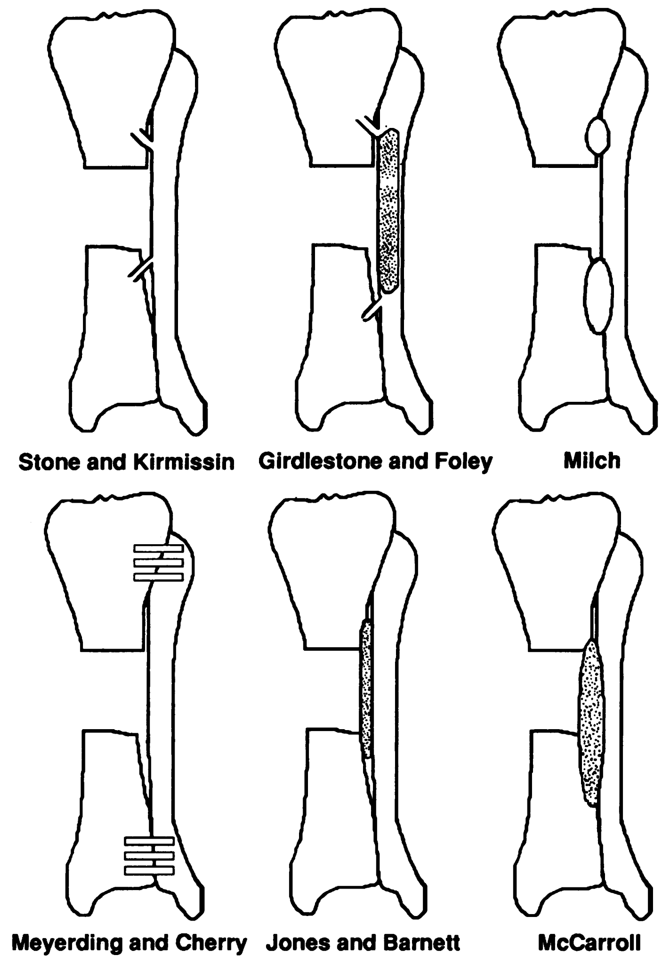

Figure 3
Various tibio-fibular synostoses. Stone and Kirmissin split the fibula and transferred the split portion onto holes in the tibia. Girdlestone and Foley created proximal and distal "flying buttress" grafts between the tibia and fibula and reinforced the fibular shaft with cancellous graft. Milch split the outer tibial cortex and laid it on the interosseous membrane. Meyerding and Cherry used bone pegs to create proximal and distal tibiofibular synostoses. Jones and Barnett recommended a posterolateral graft; McCarroll advocated an anterolateral graft.

Free non-vascularized graft

Free non-vascularized fibular graft, as well as free tibial and iliac graft, has been employed in both inlay and onlay fashion with a variety of fixation techniques to bridge bony defects.[25] While a whole fibular transplant is almost ideal for bridging defects of the radius or ulna, elsewhere single fibular transplants are limited by their size. The graft needs prolonged support and will continue to weaken as it revascularizes, reaching a maximum weakness in twelve to forty-eight weeks after transfer.[31] In addition, these grafts are too small and prone to fatigue fracture in the adult tibia; however, in children, fibular grafts may hypertrophy enough to approach the size and strength of a normal tibia.[9]

One exception to the application of free nonvascularized fibula in the adult lower extremity is its use in dual fashion.[41] Significant tibial and femoral gaps of up to twenty-four cm have been successfully bridged in adults following intercalary resection of a low grade tumor. Nonunions and fatigue fractures occurred occasionally and universally healed after local autogenous grafting. This technique appears to be simple, readily available, reliable, less time consuming and economical compared to some other techniques (no need for a bone bank, microvascular expertise, expensive implants, etc.)

Free vascularized graft

Free vascularized bone graft was first described by Taylor in 1975. Orthopaedic literature has largely dealt with application of free vascularized fibulae in the management of congenital pseudoarthrosis in the tibia. Generally, excellent results are reported.[35,40] Vascularized fibular pedicle grafts[13] and cross leg composite pedicle grafts[12] have also been described for management of this condition.

Free vascularized bone grafting has been successfully applied to segmental bone defects of up to fifteen cm secondary to infection, trauma or following tumor resection.[24,38,39] Donor sites employed most frequently are the fibula (most suitable for reconstitution of long bone defects), rib and iliac crest, the latter being part of an osteocutaneous transfer.

Such free grafts retain their intrinsic nutrient blood supply so that osteocytes in the graft can survive.

Healing of the graft to recipient bone will be facilitated without the usual replacement of the graft itself by creeping substitution. Advantages include quicker union at the graft-host junction, shorter immobilization, improved graft incorporation and graft hypertrophy. The cortical nature of the bone also allows for stable internal fixation and early progressive weight bearing.[31] In addition, vascularized grafts may be suitable for transfer into poorly vascularized beds.[30] Disadvantages include potential donor site morbidity, prolonged and complicated surgery, and need for microvascular expertise and equipment.

Autoclaved Autograft

This technique has been employed for limb salvage following wide local resection for low grade and certain high grade malignant lesions.[22] Following excision of the lesion, gross tumor is debrided and the remaining bone is autoclaved for five minutes to kill microscopic tumor deposits. The bone is then reimplanted with some form of internal fixation and/or prosthetic implant. Segmental defects ranging from ten to eighteen cm of the distal femur and ten to thirteen cm of the proximal tibia have been reconstructed with a long stem total knee prosthesis supplemented by autoclaved autogenous bone graft. Infection, delayed wound healing or tumor recurrence have not been problems. The autoclaved graft is easily obtained and always has a perfect fit. Though the technique is appealing, in vivo biopsies of the graft have revealed no incorporation of dead bone and, experimentally, autoclaved autograft heals slower than fresh autograft or fresh frozen allograft.

Allograft

The first large series of allograft transplantation was reported in 1908 by Lexor who performed whole and hemijoint transplants about the knee with limited success. It was not until the 1960's, when it was discovered that the immunogenicity of the graft could be reduced by freezing, that interest in allograft transplantation was rekindled.[29]

The use of allograft bone in the reconstruction of segmental defects may offer some distinct advantages. The supply of bone is relatively unlimited and available in a variety of sizes and shapes. Allografts do not require sacrifice of normal structures nor is there donor site morbidity. With cryopreservation techniques, articular surfaces can be retained in the anatomical reconstruction of the joint (osteoarticular allograft), or allograft can be used in conjunction with a prosthesis ("alloprosthesis"). Conversely, autograft bone is of limited supply, and the shape of the material, its relative lack of strength, and the absence of articulating surface often make it impossible to construct massive defects.[29]

Observations on massive retrieved human allograft[11] have demonstrated consistent union at the graft-host junction. Internal repair is slow and confined to the ends and superficial surface of the graft, and involves approximately 20% of the graft by five years. Deep unrepaired portions of the graft retain their architecture. When an implant was used, no evidence of resorption or loosening was noticed. Soft tissues of the host attached to the graft by deposition of a thin seam of new bone on the surface of the graft. In osteoarticular autografts, necrotic cartilage functioned well for as long as five years. This method is generally employed following tumor resection, though has been used for non-neoplastic conditions including failed total hip arthroplasty,[32] extensive fibrous dysplasia or Gaucher's disease.

Despite enthusiasm in many published reports, use of allograft bone has certain disadvantages. Revascularization is even slower than that of autogenous cortical bone. Fractures, infection, nonunion, and host versus graft reaction have remained problems. In addition, allograft bone must generally be avoided in patients with infection because any residual organisms can remain on the allograft, which acts as a large sequestrum.[31]

Xenograft

There is very little recent literature about this new rarely applied technique, though bovine graft at one time had numerous proponents. Later series showed bovine bone was poorly tolerated by the host and condemned its use in orthopaedic surgery.[18] More recently, freeze dried baboon bone combined with an autogenous component of cancellous bone has been used to reconstruct large diaphyseal defects in humans following trauma and tumor resection. The technique uses cross segments (rings) of implant material stacked on an intramedullary nail. At two years, the xenograft showed radiologic and histologic incorporation. Advantages, like allograft, include an unlimited supply of bone available in a variety of shapes and sizes.[23]

DISTRACTION OSTEOGENESIS

Ilizarov, expanding on traditional mechanical considerations of bone formation under compression, has demonstrated bone formation under tension loading.[3] This "distraction osteogenesis" or "callotasis" offers enormous potential in reconstruction of both skeletal and soft tissue defects. The technique utilizes corticotomies of varying geometry and a flexible ring external fixation unit which allows for distraction of bone segments (Figure 4). Several months are needed to regain skeletal length and to allow for maturation of woven bone formed during distraction so that unprotected loading may commence. For pure lengthening, the frame is on an average of one month (thirty days) for each one cm (ten mm) of lengthening.

Though the device is cumbersome, technically difficult to apply, and requires complex inventories of equipment and frequent manipulations during treatment, potential advantages are appealing. The technique often can be done in one stage without the need for additional bone grafting or soft tissue coverage. Skeletal length and alignment can be manipulated simultaneously, and the size of the osseous defect, in theory, presents no impediment.[31]

BIOMATERIALS

Demineralized Bone Matrix

Based on animals studies, several authors[5,10] have considered the use of demineralized bone matrix (DMB) as a graft in clinical situations for repair of segmental defects. These studies have consistently demonstrated osteoinduction (chemotaxis of progenitor cells and their attachment to demineralized matrix), followed by formation of a cartilagenous matrix (which undergoes calcification, replacement by osteoid and mineralization). Advantages of DMB include ease of preparation, abundant supply, long storage life, and, at least experimentally,

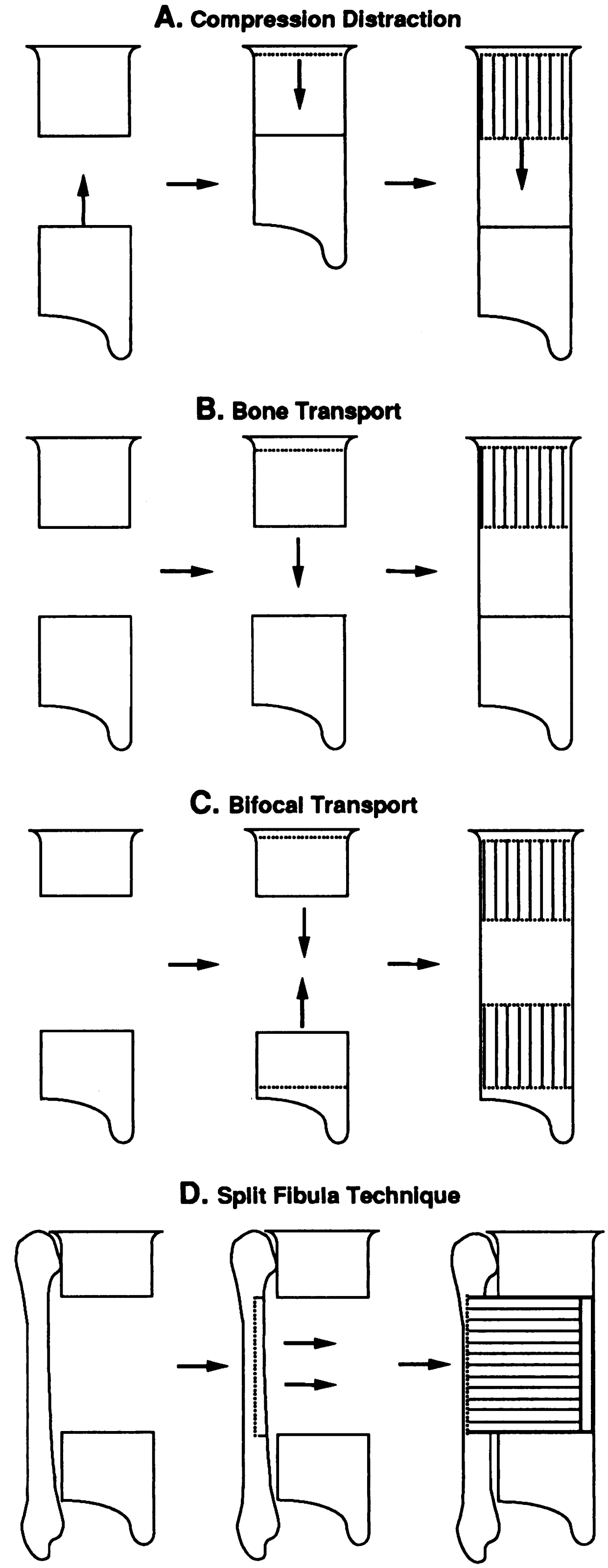

Figure 4
Distraction osteogenesis. Dashed lines represent corticotomy sites; lined regions depict new bone trailing the transported segment(s).

induction of bone that biomechanically behaves like bone observed in the early stages of normal fracture repair[10] or bone formed after autogenous cancellous grafting.[5] Use of DMB would reduce the morbidity associated with autogenous graft harvest and have a likely advantage over bulk autograft is probably never fully incorporated by the host. No series have described the use of DMB for reconstruction of human diaphyseal defects, though DMB has been used successfully in human craniofacial reconstruction and spinal fusion.

Ceramics

Alumina ceramics have good biocompatibility and high mechanical strength. These materials have been used for articulating surfaces in total hip arthroplasty, segmental replacements of long bone defects, and vertebral body replacements. These ceramics do not form a chemical bond with osseous tissue and are prone to loosening at the bone-implant interface. Calcium phosphate ceramics (hydroxyapatite, tricalcium phosphate) form tight chemical bonds with osseous tissue. Their low mechanical strength has limited their use to non-weightbearing structures, filling defects, or coating of hip prostheses.

A glass ceramic containing apatite and wollastonite has been created which has high mechanical strength as well as ability to form a chemical bond with bone. This material has been successfully applied to long bone defects experimentally created in a rabbit model[36] but, like DMB, no series have described its clinical application to human long bone defects.

Prosthetic Implants

Noncoated, cemented, custom and modular implants have been widely used about the knee following segmental tumor resection. Because all ligament constraint at the knee joint is removed, a hinged prosthesis has to be used in the basic design. Fixation to bone of the long component remains the most critical problem, and coated implants (e.g., fiber metal, hydroxyapatite) may provide more satisfactory long term fixation.[36]

Failure of total knee prostheses, particularly fixed hinged devices, may result in substantial bone loss. Revision components can include elongated femoral or tibial stems to make up for lost bone stock. Revision to another hinged device resulted in high complication rates (fracture, subsequent loosening) in one study. The authors recommended use of uncemented or partially cemented nonfixed hinges that are compatible with bone grafting to restore lost bone stock.[21]

Anderson[2] demonstrated successful segmental replacement of long bone defects in baboons using an intercalary fiber titanium implant. Uninterrupted bone formation occurred along the full length of the replacement segment in 70% of the defects created by extraperiosteal resection and supplemental bone graft and in 71% of the subperiostially resected defects without grafts. No bone formation was noted in any defects after extraperiosteal resection without bone grafts.

Kuo[27] applied a similar titanium fiber metal implant for human segmental defects following tumor resections about the knee. The procedure was done in one or two stages and included supplemental cancellous bone grafts packed around the fiber mental implant. The technique, used as a diaphyseal segmental arthroplasty or knee arthrodesis for defects ranging from 9.5 to 18 cm, resulted in a stable weight bearing extremity in sixteen of seventeen patients.

DISCUSSION

Research and new technology have provided an array of effective techniques for the reconstruction of long bone defects. A fundamental question, however, must be addressed prior to embarking on often technically difficult, time consuming, expensive reconstructions that may be associated with high complication rates and patient dissatisfaction: Is the limb worth saving? Multiple factors including etiology of bone loss, age of the patient, site and extent of bone and soft tissue damage, state of distal limb including vascularity and innervation, as well as psychosocial and economic factors are all important. The surgeon also must view aims of treatment from the patient's perspective. These include creation of stable, painless, discharge-free limb that has satisfactory joint motion, muscle power, sensation and, in the lower extremity, length. Treatment time should be minimal and weight bearing should commence early. Clearly, each candidate for reconstruction must be individualized based on careful assessment of all variables.

Retrospective studies have provided certain guidelines for limb salvage (versus amputation) with respect to underlying pathology. Various scoring systems based on duration of ischemia, age, preexisting disease, shock, level of arterial injury, degree of bony/soft tissue injury, etc., have been useful in decision making in massive lower extremity trauma.[16,19,20] Certainly strong arguments favoring primary amputation of the Type IIIC open tibial fracture exist.[7,17] With respect to primary sarcomas of the extremities, limb sparing technology should in no way affect the ultimate survival of the patient compared to traditional amputation. At the same time, the patient should be left with a functional capacity equal to or better than the same patient with an amputation and prosthetic limb.[22] In certain congenital defects, efforts at saving the limb may be inadvisable. For example, amputation may be indicated in management of congenital pseudarthrosis of the tibia after repeated operative failures, when the prognosis is poor, when significant deformity exists or when there is excessive leg length discrepancy.[34]

The decision, therefore, is often one between amputation and early prosthetic fitting versus reconstruction of soft tissue and bone. When informed of the potential duration of treatment and associated risks, some patients elect amputation rather than reconstruction. If reconstruction is chosen, it is important to emphasize to the patient early in the course of management that failure can occur at any stage, and other options, including further efforts at reconstruction or amputation, may be elected.

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